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CLAY MINERALOGY, FABRIC, AND INDUSTRIAL USES OF THE SHALE OF THE DECORAH FORMATION, SOUTHEASTERN MINNESOTA

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ABSTRACT

The Decorah shale varies both vertically and laterally in its clay mineral assemblages. It is principally an illitic shale in Minnesota, but kaolinite is approximately of equal abundance in the basal part to the southwest, reflecting nearness to the source area, most probably the Transcontinental Arch. Lateral variations in clay mineral assemblages of the Decorah are similar to that of the coextensive older Ordovician Glenwood Formation, suggesting that the source was the same and that both were deposited under similar conditions. The vertical variation in clay mineral assemblages in the Decorah shale, from kaolinite and illite toward the base to only illite in the upper part, reflects the transgressive nature of the Decorah sea.

Certain engineering properties of the Decorah shale are related to the orientation of clay minerals. The shale is relatively impermeable perpendicular to bedding where the clay minerals are arranged with their shortest axis normal to the bedding surface, as in a deck-of-cards arrangement, but is permeable parallel to bedding. In contrast, a random clay mineral arrangement, as in the card-house structure, is permeable in all directions. Both types of clay mineral arrangements are present in the Decorah shale. Maintaining the natural moisture content of the Decorah shale during and after construction aids in stabilizing slopes and foundation bases.

The clay mineral data suggest that the Decorah shale may be satisfactory for use in ceramic products such as face brick, sewer pipe, lightweight aggregate, structural tile, and drain tile. Numerous areas along the shale's outcrop belt in southeastern Minnesota would be satisfactory for open pit mining.

INTRODUCTION

The thickest and most widespread shale of Paleozoic age in Minnesota is in the Ordovician Decorah Formation. This shale has served as raw material for production of face brick in the State for many years, but its full potential as a useful industrial mineral has not yet been realized. Because knowledge of the clay mineralogy of a shale is of prime importance in evaluating its usefulness as an industrial mineral resource, a study was undertaken to determine the vertical and lateral variations in the mineralogy of the clay mineral assemblages within the Decorah in Minnesota. The Decorah Formation is overlain by younger sediments in parts of southeastern Minnesota, and where these deposits are thin, the shale often is exposed during road and foundation construction. The behavior of the shale in certain of these engineering projects provides some understanding of the engineering properties of this rock unit, which can be applied in turn to future building projects. The information on clay mineralogy and on some of the rock's physical properties, moreover, is more meaningful when correlated with its geologic history. Therefore, these three subjects, clay mineralogy, geologic history, and physical properties, are combined in this study of the Decorah shale. For more detailed stratigraphic and lithologic descriptions of this unit, the reader should refer to Agnew (1956), Agnew and Sloan (1956), Grout and Soper (1919), Sloan and Weiss (1956), Stauffer and Thiel (1941), Thiel (1944), Webers (1966), Weiss and Bell (1956), and Weiss (1957).

The Decorah Formation of southeastern Minnesota is underlain by the Ordovician Platteville Formation and overlain by the Ordovician Galena Formation, both predominately carbonate lithic units. The thickness of the Decorah varies from about 95 feet in the north to about 25 feet in the southeast. It has a gray-green to blue-green color and contains thin layers of gray limestone. Limestone layers are more abundant and thicker in the shale's upper part, where individual beds may reach 2 feet in thickness. The carbonate layers are generally coquinoid; the shaly portion also contains marine fossils. Orthoclase has been identified as a probable authigenic mineral in the Decorah shale (Gruner and Thiel, 1937). Small, broad x-ray reflections at 3.24Å in the less-than-2-micron fraction of samples studied by us further confirms the presence of a potassium feldspar. Traces of quartz and calcite also are present locally in this size fraction. A 3/4 to 1 1/2 inch, soft, light-gray potassium bentonite (K-bentonite) has been recognized at many localities within the basal 7 feet of the Decorah Formation. Details of the mineralogy of this K-bentonite and others of somewhat higher and lower stratigraphic position within the Ordovician section have been discussed by Mossler and Hayes (1966). The clay mineralogy of the K-bentonites in our study fits the description of a "randomly interstratified mica-montmorillonite" of Mossler and Hayes (1966).

PROCEDURE

Samples were collected from 27 localities in southeastern Minnesota and one locality in northeastern Iowa (figure 1 and the appendix). Samples

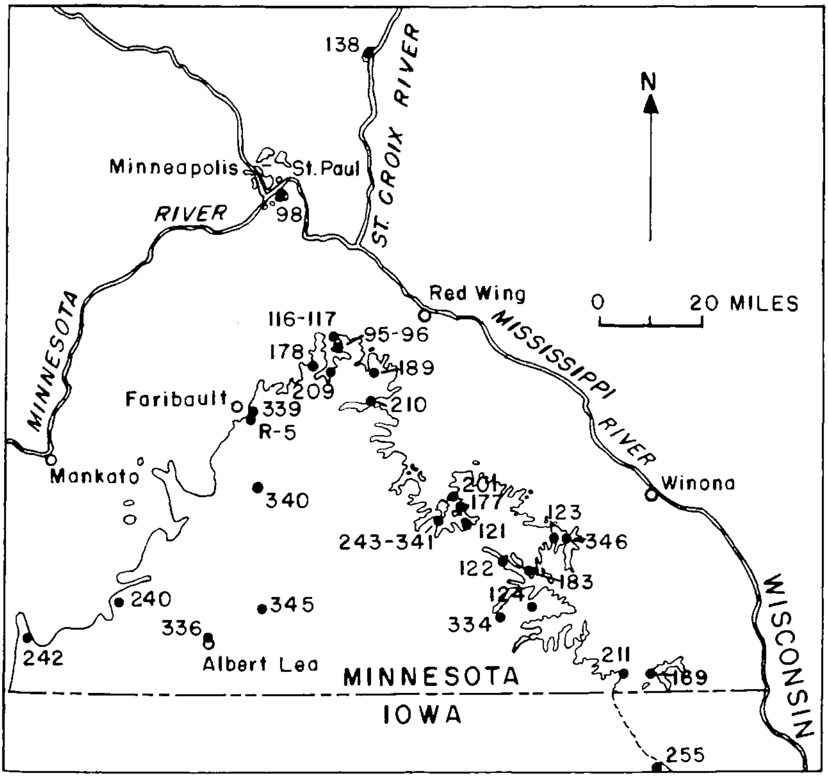

Figure 1--Map showing outline of the Decorah Formation and sample localities.

from southwestern localities, where the shale is covered, were taken from drill cuttings and cores. The erosional edge of the shale outcrop and subcrop is shown in figure 1. Vertical samples of the shale were taken at each locality; the sample interval is listed in the appendix.

Samples for x-ray analysis were gently disaggregated and allowed to slake in distilled water; those that flocculated were dispersed by washing with distilled water. In some cases where severe flocculation occurred, Calgon was used to obtain a clay dispersion. Oriented aggregates of the less-than-2-micron fraction obtained by sedimentation were prepared on glass slides and dried at room temperature. X-ray diffraction data were obtained first on air-dried clay slides; they were x-rayed again after each slide had been placed in an ethylene glycol atmosphere for approximately 24 hours to facilitate identification of expansible clay minerals. The slides were heated to 480° C. in a small electric muffle furnace for one hour when it was difficult to distinguish chlorite from kaolinite. Heat treatment removed diffraction peaks from the record for kaolinite and left those for chlorite. Nickel-filtered copper radiation was used throughout the study; machine settings of 40 KV, 20 ma, and a goniometer speed of 2 degrees 2θ per minute were used.

Six x-ray records that illustrate the range in composition of the clay-size fraction of the Decorah shale are shown in figure 2. The six x-ray records, here referred to as type curves, are arranged so that the kaolinite peaks decrease in intensity with respect to illite from curve A through curve D. Curve D contains chlorite peaks in addition to those of kaolinite and illite. Curve E consists of only chlorite and illite and curve F is of illite alone. Illite is the most common clay mineral present in all curves; kaolinite may approximate illite in abundance, be present in lesser quantities, or be absent. Chlorite may be present either in small amounts or be absent. A small amount of expansible random mixed-layer clay material may be present.

X-ray records for each sample were compared to the six type curves, A, B, C, D, E, and F, and assigned the letter of the type curve they most closely resembled. The letters representing type curves are listed for individual samples in the appendix, and were used in construction of cross sections X-X' and Y-Y' in figure 3 and in construction of figures 5-A and 5-B.

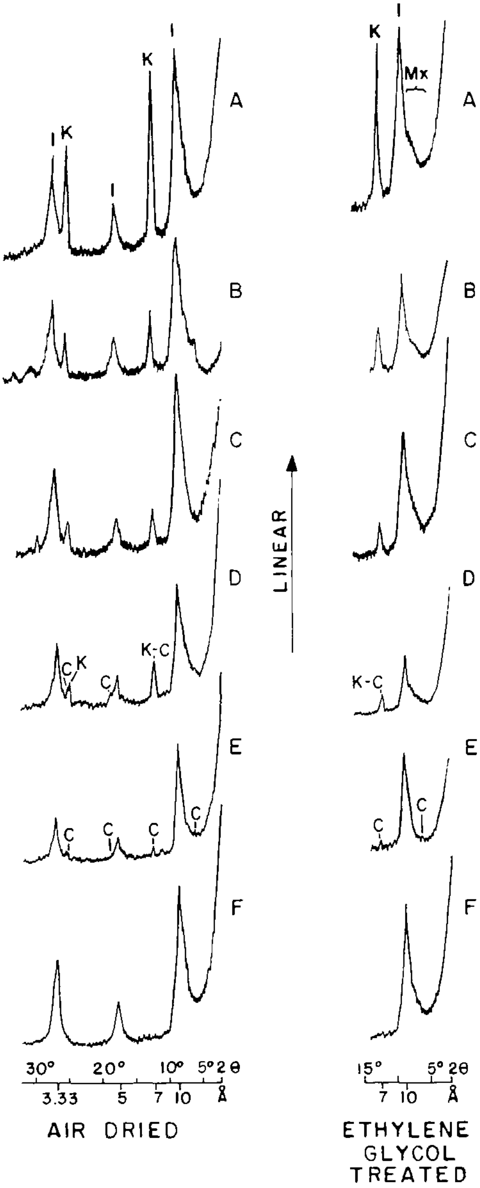

Figure 2--Type clay mineral x-ray curves of the less-than-2-micron fraction of the Decorah shale.

CLAY MINERALOGY

Clay mineral assemblages of the Decorah shale in Minnesota vary both laterally and vertically in a relatively orderly manner. Within the sampled area, kaolinite is most common to the southwest and gradually decreases in abundance laterally to the northeast until it is absent. Illite shows the inverse relationship; that is, it is most abundant in the northeast and less abundant to the southwest. Chlorite is a minor constituent in the shale and occurs in intermediate positions between the kaolinite-rich areas of the southwest and the illite-dominated area to the northeast. In the vertical dimension, illite is the principal clay mineral in the shale; if present, kaolinite occurs in the lower part of the shale.

Figure 3 shows the three dimensional changes in clay mineral assemblages in the Decorah shale. Section X-X', assumed generally perpendicular to depositional strike, extends from southwest to northeast, and section Y-Y' extends from northwest to southeast. Section X-X' shows that kaolinite decreases in abundance from southwest to northeast and also from the base of the shale upwards. Section Y-Y', however, shows that illite is the only clay mineral present in sections other than sample 201; there are small amounts of chlorite present in parts of this section. The same lateral relationship of kaolinite and illite has been found also in the Ordovician Glenwood Formation of southeastern Minnesota (Parham and Austin, 1967), and an up-dated map of the lateral changes of abundances of the two minerals in the Glenwood shale is shown in figure 4.

A review of the literature has shown that in sedimentary basins kaolinite commonly accumulates or has accumulated closer to shore with respect to illite, illite reaches maximum abundance seaward of kaolinite, and chlorite, where present, occupies an intermediate position between the two (Parham, 1966). Consideration of the lateral distribution of clay minerals in the Glenwood Formation suggests to us that the source for the clay minerals present in this unit most probably was the Transcontinental Arch, lying to the west or southwest. Lateral changes in clay mineral assemblages in the Decorah shale also suggest a predominantly southwesterly source area for its sediment, and it seems probable that the source was a part of the Transcontinental Arch.

The kaolinite in both shales may have been derived from erosion of either pre-existing kaolinitic sedimentary rocks or from kaolinitic weathering products developed on the Transcontinental Arch. Pre-

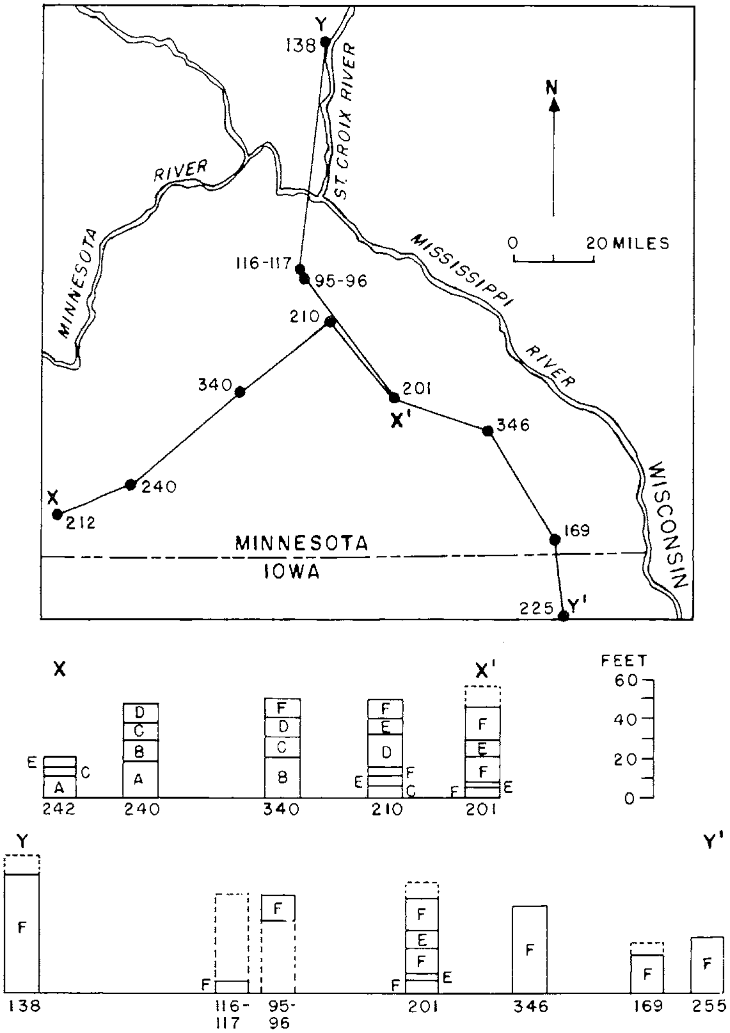

Figure 3--Sections X-X' and Y-Y' of the Decorah Formation, showing variations in the clay mineral assemblages.

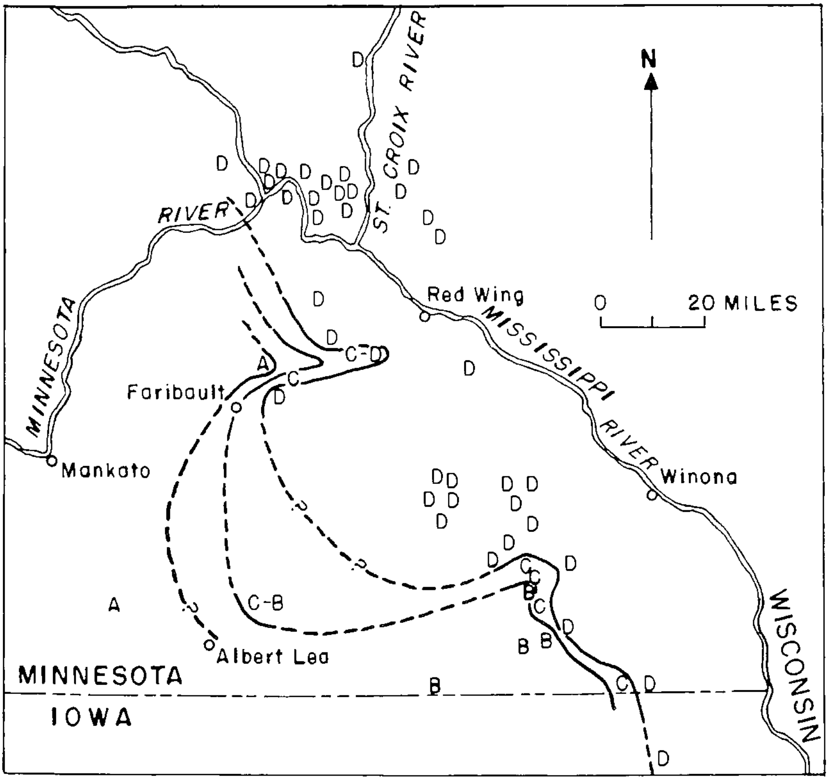

Figure 4--Relative abundance and distribution of kaolinite and illite in the Glenwood shale.

Pleistocene erosion has removed much of the two shales, narrowing the lateral extent of each; however, it seems reasonable that the eroded part of each, to the southwest, probably was more kaolinitic than the samples represented by type A curves. The decrease in kaolinite upward suggests that the sea was transgressive while the shale was being deposited. Figures 5-A and 5-B are generalized diagrams showing gross variations in clay mineral assemblages of the lower and upper part respectively of the Decorah Formation.

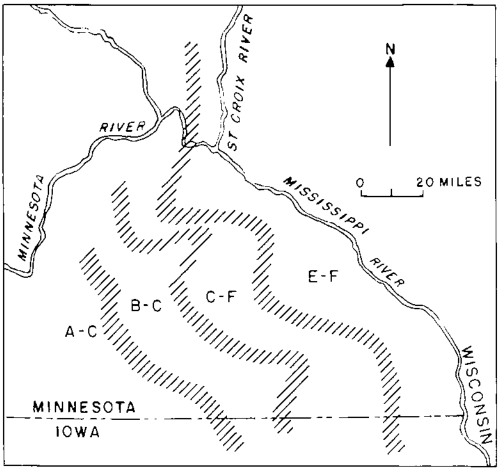

Figure 5-A--Generalized clay mineralogy based on type x-ray curves of the lower part of the Decorah Formation.

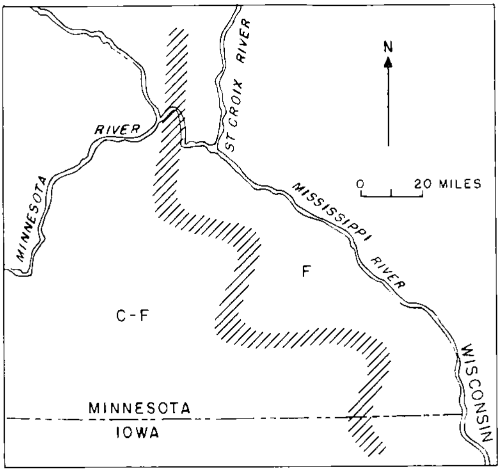

Figure 5-B--Generalized clay mineralogy based on type x-ray curves of the upper part of the Decorah Formation.

The Platteville-Decorah contact generally has been placed above the last thick carbonate bed at the top of the Platteville Formation and below the overlying thick shale. Our data has shown in a few places (localities R-5, 336, and 339) that the greatest concentration of kaolinite may not occur at this stratigraphic position, but rather one or two feet higher in the shale. It is our interpretation that the first one or two feet of shale may have been produced under conditions similar to those that produced the thin illitic shale beds in the Carimona Member of the Platteville Formation (Rassam, 1967). Therefore, it seems probable that there are certain instances where environmental conditions produced a shale-on-shale contact between the two formations. Because recognition of such a contact is difficult, it still seems most practical to place the contact as before at the top of the last thick limestone bed, remembering that the first few feet of shale may represent a depositional site farther from shore than the kaolinitic shale immediately above.

FABRIC

The fabric of the Decorah shale controls to a large extent certain of its engineering properties. Throughout southeastern Minnesota the shale often is exposed during construction and must serve as bedrock for various foundations. The stability or instability of roads and cuts constructed on or through the shale can be related to the fabric of the clay mineral assemblage comprising the rock unit. Our study of the various clay mineral assemblages found in the shale shows that expansible clay minerals, such as montmorillonite, generally are of minor abundance,thus eliminating a mineralogical control to the engineering properties.

It is well documented that preferred orientation of clay minerals, or the lack of it in unmetamorphosed clays or shales, is not a function of rock age or depth of burial (Grim, Bradley, and White, 1957; Gipson, 1966; Meade, 1966; and Odom, 1967). Because most of the common clay minerals are plate-like in shape, they can be arranged within the sediment or sedimentary rock much like a deck of cards or randomly oriented as in a card-house arrangement. Between these two extremes lie all possible degrees of preferred clay mineral orientation. Where platy clay minerals lie generally parallel to a bedding plane, as in the deck-of-cards arrangement, the resulting shale will break most commonly along smooth surfaces parallel to the bedding plane. This type of clay mineral orientation is present in parts of the Decorah shale and is accompanied locally by the presence of brachiopods and bryozoa that have their shortest dimension oriented perpendicular to bedding. More equidimensional fossil types generally are crushed and flattened, with the flattened surfaces oriented perpendicular to bedding. Figure 6 is an electron micrograph of a replica of a smooth bedding-plane surface of the Decorah shale on which most of the clay minerals are oriented with their shortest dimension normal to the plane of the photograph. Figure 7 is an electron micrograph of a replica of a surface of the same sample of Decorah shale shown in figure 6, viewed parallel to the bedding plane. Comparison of these two electron micrographs shows the effect preferred orientation of clay minerals has on development of good bedding in shale.

The card-house arrangement of clay minerals also is present within the Decorah shale. Because of the lack of preferred clay mineral orientation, the shale having the card-house arrangement will not break smoothly parallel to the normal bedding direction but instead will break along irregular surfaces. This clay mineral arrangement is further characterized by the presence of randomly oriented, small-scale slickensides (figure 8), formed during initial stages of compaction (White, 1961). Figure 9 is an electron micrograph of a replica of a slickenside surface in the Decorah shale on which there is a high degree of preferred clay mineral orientation. In general, the fossils within shales having the card-house arrangement lack a preferred orientation with respect to the normal bedding-plane directions. In addition, crushing of more equidimensional fossils is uncommon within shales having this type of clay mineral arrangement, even though fossil fragments may be present.

Development of parallel versus random orientation of clay minerals in the Decorah shale is interpreted as being a function of rate of accumulation of sediment. The flocculation of clays entering a marine environment has long been recognized (Brewer, 1885). It is assumed from the abundant marine fossils present in the Decorah shale that the clays which formed this shale were deposited in a flocculated state (card-house arrangement), with individual clay minerals randomly oriented with respect to one another. During periods of rapid sediment accumulation, individual clay mineral flocs settle to the sea floor and collapse under the weight of the rapidly accumulating, additional flocculated clay material above. Collapse of individual clay mineral flocs results in an arrangement of platy clay minerals in which the shortest dimension of each is oriented approximately perpendicular to the bedding surface of the sea floor (deck-of-cards

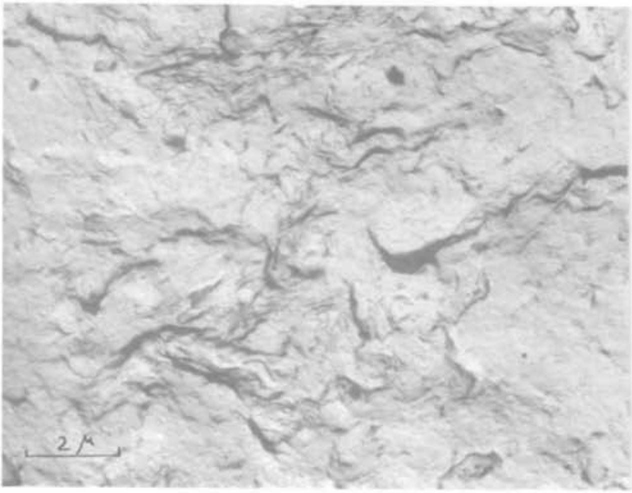

Figure 6--Electron micrograph of a replica of a bedding-plane surface of the Decorah shale on which most of the clay minerals are oriented with their flat surfaces parallel to the bedding plane.

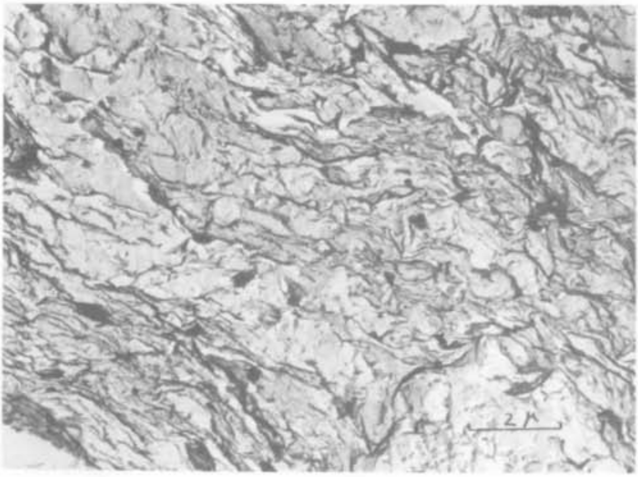

Figure 7--Electron micrograph of a replica taken at right angle to figure 6. Preferred orientation of clay minerals marks bedding-plane direction.

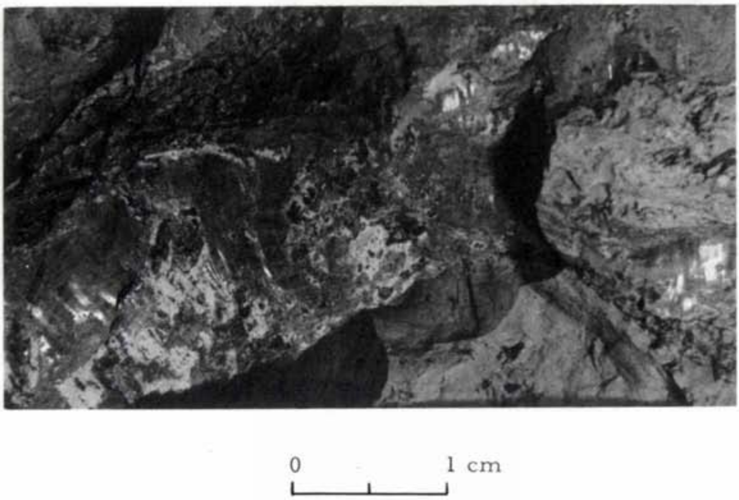

Figure 8--Slickensides (areas of high reflection) in Decorah shale. Photograph taken at right angle to expected bedding plane. Rough surface and presence of slickensides is indicative of lack of preferred clay mineral orientation within this sample.

arrangement). During time of rapid sediment accumulation, and thus times of floc collapse, animal remains within the muddy sediments would be reoriented so that their shortest axis would also be essentially perpendicular to the bedding surface. As the platy clay minerals are pressed closer together, enclosed animal remains, such as brachiopod shells, would collapse.

During periods of slow sediment accumulation, bonds between clay minerals develop strength within individual flocs and also between clay minerals in adjacent flocs (Terzaghi, 1941; Hamilton,

Figure 9--Electron micrograph of a replica of a slickenside surface in Decorah shale. The clay minerals show a high degree of preferred orientation on slickenside surfaces.

1964). If the rate of sediment accumulation remains low for extended periods of time, the muddy sediment will develop an overall resistance to shear as clay mineral bonds become stronger (Moore, 1964). Fossil remains, preserved in clay-rich sediments that have accumulated slowly, will lack preferred orientation of their shortest axis with respect to the usual horizontal bedding-plane surface. In addition, after the flocculated clay sediment has developed a certain amount of resistance to shear, the animal remains within the sediment will be protected from crushing even after the rate of sediment accumulation has increased again. Plastic clays with this card-house arrangement of clay minerals are present today in sediments at least as old as Cambrian age (Boswell, 1961).

Without further examination of the shale we might conclude at this point that the effect of clay mineral orientation on permeability should be pronounced. A simple experiment shows this to be true. A sample of air-dried Decorah shale exhibiting good bedding characteristics is shown in figures 10-A and 10-B after a drop of water had been placed on the bedding surface. Photograph 10-A was taken after two seconds and photograph 10-B after 90 seconds. Within this time interval, the shale is relatively waterproof perpendicular to bedding or perpendicular to the top of the clay minerals having a deck-of-cards arrangement. Figures 11-A, 11-B, and 11-C, taken at 4, 15, and 45 seconds respectively, are of the same sample viewed beneath water. The photographs were taken parallel to the bedding plane and show a large expansion perpendicular to that plane. It is evident that the shale sample is highly permeable in this direction, that is, in the direction perpendicular to the edge of the deck-of-cards arrangement. It should be noted in this set of photographs that the water-proof surface of the bedding plane remains intact as the shale sample expands and breaks down, illustrating aniostropic permeability. Destruction of the shale sample takes place as water moves in between the platy clay minerals, prying them apart and causing expansion of the rock as a whole perpendicular to the bedding direction. Emerson (1967) has suggested that in air-dried, clay-rich soils water moves into the soil structure by capillary action driving entrapped air ahead into constricted spaces. The air exerts increasing pressure on smaller and smaller surface areas as it is compressed by advancing water. This force can normally pry clay mineral contacts apart unless the contact is cemented or the clay minerals are extremely thin and flexible. A prying action of this type in a shale in which there is a high degree of preferred clay mineral orientation parallel to the bedding plane causes expansion normal to that bedding surface. Water movement into an air-dried clay in which there is random orientation of clay minerals should result in small but equal expansion in all directions.

The ability of the Decorah shale to maintain a constant angle of slope in road cuts is partly a function of whether or not the natural moisture content of the shale is held constant during and after construction. When fresh cuts in the Decorah shale are exposed to air and sunlight the natural moisture content of the rock is reduced and air is able to move into spaces between the clay minerals. During the next rainfall the air-dried shale will behave as shown in figures 11-A, 11-B, and 11-C. The shale will take water into its structure, expand rapidly, and disaggregate within a short time. Pieces of shale, loosened by the swelling action, move down slope exposing additional fresh material. The newly exposed shale dries, and

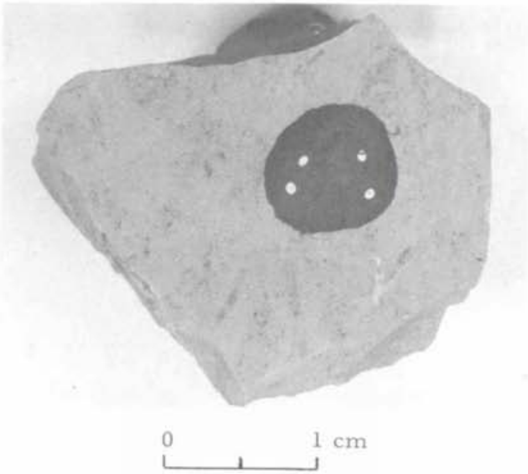

Figure 10-A--Drop of water on Decorah shale bedding-plane surface after 2 seconds. Platy clay minerals are aligned parallel to bedding surface. Sample is air dried.

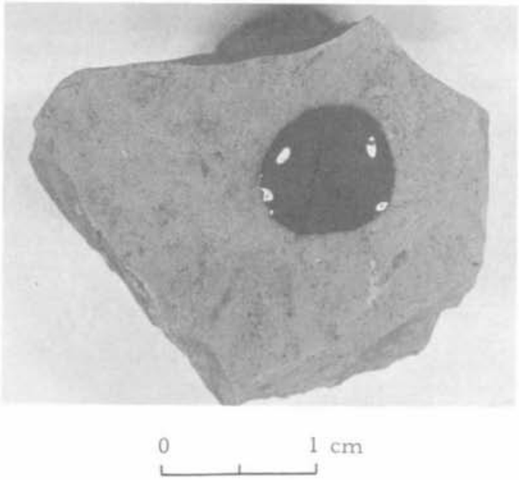

Figure 10-B--Drop of water on Decorah shale bedding-plane surface after 90 seconds. Water drop is slowly evaporating from heat of photographic lights. Water movement into the shale sample is negligible.

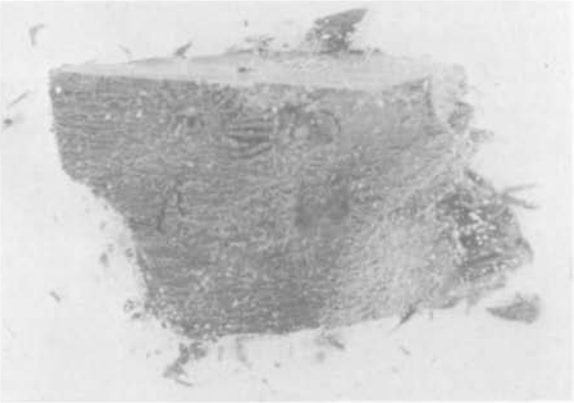

Figure 11-A--Same sample of Decorah shale as in figures 10-A and 10-B photographed after submergence in water for 4 seconds. View essentially parallel to bedding-plane surface. Movement of water between clay minerals arranged in deck-of-cards fashion occurs rapidly. Maximum direction of expansion of the shale is normal to bedding.

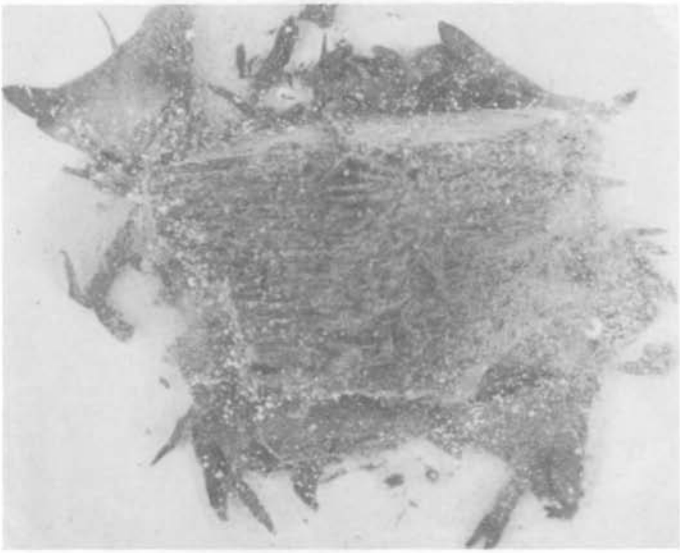

Figure 11-B--Same view as in figure 11-A but after 15 seconds elapsed time. Shale is breaking up parallel to bedding plane as water drives out entrapped air.

Figure 11-C. Decorah shale sample after 45 seconds elapsed time under water. Note that original bedding surface is still preserved because of its impermeable nature.

during the next rainfall the swelling and erosion cycle is repeated. If, on the other hand, the shale slope can be covered quickly to prevent drying, the likelihood of developing chronic sliding conditions will be reduced.

Foundation construction in the Decorah shale is subject to the same problem arising from drying and rewetting of freshly exposed shale as in road cuts. If the shale is exposed in excavations or trenches sufficiently long for the drying-wetting cycle to take place before concrete is poured, considerable sloughing and caving of the shale walls probably will occur. In addition, the bottom of the excavation will become soft and result in a reduction of bearing strength. Efforts to keep the natural moisture content of the shale stable until foundation construction is complete should be of considerable help in avoiding these problems.

When the overlying cover is thin, it might be expected that the Decorah shale would be subjected to drying and wetting cycles, thus reducing the competency of the shale in the upper part. Movement of water out of the shale has already been shown to be more common parallel to bedding planes and less common upward or at right angles to bedding. A certain amount of natural moisture of the shale would likely escape upward from near-surface zones within the shale where the card-house clay mineral arrangement exists. Zones of random clay mineral orientation in the Decorah shale alternate over small stratigraphic intervals with zones having a high degree of preferred clay mineral orientation. It may be assumed, therefore, that the direction of maximum water movement through the shale on drying will be lateral rather than vertical. A thin layer of well-bedded shale at or near the surface acts to retard movement of water vertically either into or out of the shale. It seems likely, therefore, that vertical expansion problems caused by the Decorah shale would be minimal in situations where foundations are completed in a thin cover of sediment just above the shale surface.

Effects of pre-Pleistocene weathering often are noticeable in the upper several feet of the Decorah Formation. The color of the weathered shale generally is some shade of buff or yellow rather than its normal gray-green color. As a result of the weathering, the shale's original fabric often is partly destroyed, and it lacks the bedding characteristics of the fresh shale beneath. When wet, the weathered shale is likely to be soft and behave more like a soil or clay than rock and therefore is not desirable as bedrock for foundation construction. Penetration resistance tests are frequently helpful in differentiating weathered shale from its fresh counterpart below.

Certain situations have arisen in Minnesota in which foundations for heavy construction rest a short distance above the K-bentonite found near the base of the Decorah Formation. The K-bentonite, though thin, at times may act as a shear plane between the shale above and that below when horizontal stresses become large, and in other instances where vertical loads are large a "squeezing out" of the K-bentonite may occur (G. R. Ford and G. R. Cochran, Minn. Highway Dept., personal communications). The low shear strength of the K-bentonite is a function of its clay mineralogy. Because the K-bentonite normally occurs in the lower seven feet of the Decorah Formation, it may be advisable in heavy construction projects involving this stratigraphic interval for supporting structures to penetrate below the K-bentonite which occurs in the upper part of the Platteville Formation.

Shales composed chiefly of illite and lesser amounts of kaolinite, chlorite, and coarse stony material are the most common source of raw material for brick (Grim, 1962). The presence of "large amounts of iron, alkalies and alkaline earths. . . are detrimental because they cause too much shrinkage and reduce the vitrification range. Thus, a clay with a substantial amount of calcareous material is not desirable" (Grim, 1962).

INDUSTRIAL USES

The Decorah shale is presently being used in Minnesota as raw material for the production of face brick. Laboratory test results on numerous samples from published reports indicate that certain of these samples would be suitable for production of lightweight aggregate (Grosh and Hamlin, 1963; Prokopovich and Schwartz, 1957; Riley, 1950). Our clay mineral data suggest that the Decorah shale from many additional localities may be satisfactory for use in ceramic products such as face brick, sewer pipe, lightweight aggregate, drain tile, and structural tile.

Brick

The clay mineral assemblages in the shale of the Decorah Formation are suitable to produce good quality brick, and the shale has been used for this purpose for many years. At the present time only the Twin City Brick Company (locality 98) is using this shale. If the many small plants that produced brick from the Decorah shale in the past ceased operations because of problems with raw material, it is probable that the reason was the presence of excessive limestone in the shale.

Procedures used to beneficiate the shale include (1) selective mining to eliminate stratigraphic intervals rich in limestone as are found typically near the top of the formation, and (2) finely grinding the shale to disperse any limestone present. The Decorah shale is a satisfactory raw material for production of brick when such precautions are taken. Brick colors produced from the shale can be varied from deep red to yellow by controlling the atmosphere in the kilns during firing, by varying the firing temperature, and by varying the amount of finely ground limestone in the clay.

The same raw materials that make good bricks commonly are suitable for production of roofing, drain, and structural tile. Although the Decorah shale is not used for tile production, it probably would be adequate for that purpose.

Sewer Pipe

Sewer pipe clays generally are composed of "illite and kaolinite frequently present in about equal amounts; a small amount of chlorite may also be present" and "relatively fine-grained unsorted quartz... in amounts ranging from 25 to 50 percent" (Grim, 1962). Relatively low shrinkage, good plasticity, and a long vitrification range are desirable characteristics for these clays. Along the outcrop belt of the Decorah Formation and in areas where it is overlain by thin cover, illite is essentially the only clay mineral present. A large amount of illite, however, would not be detrimental in production of sewer pipe. Quartz sand could be added to lower drying and firing shrinkage. The St. Peter Sandstone, a quartzose sandstone, crops out in the same general area as the Decorah shale and might be a suitable source for clean quartz sand. The Decorah shale is not used at present for producing sewer pipe, but it is a potential source of a satisfactory raw material for such a purpose.

Lightweight Aggregate

Some clays and shales expand or bloat when heated rapidly to high temperatures. Bloating is accomplished by the trapping of released gases by the viscous, partly fused clay or shale. Structural concrete produced from the resulting lightweight aggregate may have unit weights ranging from 50 to 100 lbs. per cubic foot and crushing strengths ranging from 1000 to 5000 psi. The concrete is resistant to freezing and thawing, wetting and drying, and expansion is negligible (Grim, 1962).

Schwartz and Prokopovich (1957) summarized the geographical criteria and geological conditions which make a shale economically attractive for use in lightweight aggregate production. These are:

1. location near market areas
2. presence of good transportation facilities
3. presence of cheap fuel
4. sufficient size of deposit to insure production needs for several years
5. sufficient thickness of shale and uniform bloating qualities
6. thin overburden
7. mining site above ground water table, or presence of suitable drainage conditions

Riley (1950), Prokopovich and Schwartz (1957), and Grosh and Hamlin (1963) concluded that there are numerous localities in Minnesota where the Decorah shale would satisfy these requirements for a source of raw material for lightweight aggregate. Goodhue County, where glacial drift is relatively thin and where the Decorah shale is exposed in many places, has been suggested as one such favorable area (Grosh and Hamlin, 1963).

Decolorizers

Thiel (1944) points out that extensively weathered Decorah shale, such as is found in the area east of the late Wisconsin glacial drift, behaves as a fuller's earth and is suitable for filtering and decolorizing vegetable and mineral oils. The Decorah shale has been tested by industry, and only relatively minor amounts of weathered shale within the glacial drift itself was found to be usable as a bleaching clay.

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APPENDIX

SAMPLE NUMBER	COUNTY	LOCATION[*/]	SAMPLE INTERVAL, IN FEET, ABOVE PLATTEVILLE FM.	TYPE X-RAY CURVE
98-32	Dakota	NWNE13:28-23	67.2	E
98-31			65.7	E
98-30			64.7	E
98-29			62.2	E
98-28			59.7	E
98-27			56.7	E
98-26			55.2	E
98-25			53.2	E
98-24			51.2	D
98-23			48.8	E
98-22			45.3	E
98-21			42	D
98-20			39	D
98-19			37	C
98-18			35.3	C
98-17			33.5	D
98-16			32	D
98-15			30.5	D
98-14			28.5	D
98-13			26	D
98-12			24	C
98-11			22.5	D
98-10			21.5	D
98-9			19.8	D-E
98-8			17.3	D
98-7			15.8	D
98-6			13.8	D
98-5			12.8	E
98-4			11.8	E
98-3			10.5	D
98-2			8	D
98-1			6	D
117	Goodhue	C., S edge 18: 112-17	3 - 5	F
116			0 - 3	F

121-O'	Olmstead	E1/2 21: 106-13	26.5	F
121-N'			23.5	F
121-M'			20.5	F
121-L'			17.5	F
121-K'			14.5	F
121-J'			11.5	F
121-I'			8.5	E
121-H'			5.5	F
121-G'			4.8	K**
121-F'			4.5	E
121-E'			2	E
122-S'	Olmstead	SENW28: 105-12	5.5	C
122-R'			3.5	D
122-Q'			0.0-5	C
123-Z'	Winona	C., E1/2 31: 106-10	29	F
123-Y'			25	F
123-X'			22	F
123-W'			18	F
123-V'			13	F
123-U'			8	F
123-T'			3	F
124-H'	Fillmore	NWNE9:103-11	39	F
124-G'			34	E
124-F'			29	C
124-E'			24	C
124-D'			19	C
124-C'			14	D
124-B'			9	D
124-A'			1	C
138-A	Washington	SE NW7:32-19	60	F
138-B			20	F
138-C			5	F
169-F	Houston	SE17:101-7	19	F
169-E			16	F
169-D			11	F
169-C			6	F
169-B			3	F
169-A			1	F

177-E	Olmstead	NW cor. 3: 106-13	19	F
177-D			16	F
177-C			11	F
177-B			6	F
177-A			1	F
178-F	Goodhue	NE21:111-18	75	E
178-E			68	E
178-D'			60	F
178-D			50	E
178-C'			40	C
178-C			22	C
178-B			17	F
178-A'			12	B
178-A			6	B
183-E	Olmstead	SE cor. 31: 105-11	34	F
183-D			28.5	F
183-C			23	D
183-B			16.5	C
183-A			2	C
189-D	Goodhue	N1/2NE28: 111-16	6.5	F
189-C			4.5	C-D
189-B			2.5	C
189-A			0.5	C
201-K	Olmstead	SESW24:107-14	47	F
201-J			42	F
201-I			37	F
201-H			32	F
201-G			27	E
201-F			22	F
201-E			17	F
201-D			12	F
201-C			7	E
201-B			6.3	K**
201-A			0-1.5	F

209-I	Goodhue	NESE24: 111-18	92.5	E
209-H			80.5	E
209-G			76.5	E-F
209-F			60.5	D
209-E			54.5	D-E
209-D			34.5	D-E
209-C			25	E
209-B			5	D
209-A			0-1	F
211-E	Fillmore	S1/2 15: 101-8	16.5	F
211-D			13	F
211-C			8	C-D
211-B			3	F
211-A			0.0-5	E
243-F	Olmstead	E1/2 15: 106-14	43	F
243-E			38	F
243-D			33	F
243-C			28	F
243-B			23	C
243-A			18	F
341-A			4.5	D
341-B			3.5	F
341-C			2.5	E
341-D			0-1	C
255-G	Winneshiek, Iowa	C., N line, 27:98-7	28	F
255-F			23	F
255-E			18	F
255-D			13	F
255-C			8	F
255-B			3	F
255-A			0-1	F
R-5-1	Rice	SWSWSE33: 110-20	5-10	B
R-5-2			0-5	C
339-C	Rice	NESESW33: 110-20	2.3-3.1	E
339-B			1.3-2.3	C
339-A			0.0-1.3	F

345-A	Freeborn	SESESW7: 103-19	45	F
345-B			43	F
345-C			41	F
345-D			39	F
345-E			37	C
345-F			35	C
345-G			33	C
345-H			31	C
345-I			29.5	F
345-J			28	C
345-K			26	F
345-L			24.5	F
345-M			22.5	F
345-N			21	B
345-O			19.5	B
345-P			17	B
345-Q			15	F
345-R			13	B-C
345-S			11.5	B
345-T			10	B
345-U			8	B
345-V			6	B
345-W			3	B
345-X			1	B
346-A	Winona	SE34:106-10	43.5	F
346-B			41.5	F
346-C			40	F
346-D			25.5	F
346-E			24.6	F
346-F			20	F
346-G			18	F
346-H			16	F
346-I			14	F
346-J			12	F
346-K			10	F
346-L			8	F
346-M			6	F
346-N			4	F
346-O			2	F

* Sections are designated by abbreviated notation.
Thus, NWNE 13:28-23 indicates NW1/4 NE1/4 sec. 13, T. 28 N., R. 23 W.

** Bentonite

APPENDIX

SAMPLE NUMBER	COUNTY	LOCATION*/	SAMPLE INTERVAL, IN FEET	TYPE X-RAY CURVE
			BELOW GALENA FM	
96	Goodhue	NW20:112-17	4	F
95			11	F
			ABOVE SAMPLE 210-B	
210-H	Goodhue	N1/2 21: 110-16	42	F
210-G			37	F
210-F			32	E
210-E			27	D
210-D			13	D
210-C			10	F
210-B			5	E
210-A			Within first 10 ft. above Platteville Fm.	C
			INTERVAL ABOVE	
240-A	Faribault	9:103-24	10.0 240-B	D
240-B			10.0 240-C	C
240-C			10.0 240-D	B
240-D			Basal 17'	A
			INTERVAL ABOVE	
242-A	Faribault	17:102-27	6.0 242-B	E
242-B			4.0 242-C	C
242-C			Basal 10'	A
			INTERVAL ABOVE	
334-A	Fillmore	SE cor 21: 103-12	9.0 334-B	E
334-B			10.0 334-C	D
334-C			Basal 12'	D

			INTERVAL ABOVE		
336-A	Freeborn	W1/2 NESE5: 102-21	5.0	336-B	F
336-B			5.0	336-C	C
336-C			5.0	336-D	B-C
336-D			5.0	336-E	C
336-E			5.0	336-F	B
336-F			5.0	336-G	C
336-G			5.0	336-H	B
336-H			5.0	336-I	A-B
336-I			Basal 5'		C
			INTERVAL ABOVE		
340-A	Steele	SWSENE16: 107-20	10.0	340-B	F
340-B			10.0	340-C	D
340-C			10.0	340-D	C
340-D			10.0	340-E	B
340-E			Basal 10'		B

*Sections are designated by abbreviated notation.
Thus, NWNE 13:28-23 indicates NW1/4 NE1/4 sec. 13, T. 28 N., R. 23 W.

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